

III.B.3 Integrated Injection and Mixing Systems for Diesel Fuel Reforming

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Objectives

- Develop reliable, cost-effective diesel fuel injection and mixing concepts for auto-thermal reformer (ATR) and catalytic partial oxidation reformer (CPOX) for use with solid oxide fuel cell (SOFC) auxiliary and distributed power generation systems
- Determine operating/performance limitations of various injection and mixing concepts for diesel fuel reforming
- Establish coke-tolerant fuel injection and mixing systems at minimal inlet pressures
- Perform design optimization for cost reduction and swiftly transition the injection technology to the Solid State Energy Conversion Alliance (SECA) industry teams

Approach

- Design and fabricate four promising injector concepts for performance evaluation
- Investigate various mixing devices and chamber configurations for the most uniform distribution of mixture temperature, velocity and concentration
- Characterize key flow field parameters using thermocouples and advanced laser diagnostic techniques, including statistical laser extinction tomography, Raman spectrometry and phase Doppler interferometry
- Utilize computational fluid dynamics (CFD) and finite element analysis (FEA) tools to analyze injector/mixer flow field structure and temperature distribution to help mitigate problems of auto-ignition, injector coking and carbon formation

Accomplishments

- Constructed a steam/hot air test rig for injector/mixer performance development and flow field characterization
- Completed the design and fabrication of two multipoint impingement injectors
- Completed the design and fabrication of two single-point gas-assisted injectors
- Completed the design and fabrication of two high-energy piezoelectric injectors
- Conducted CFD and FEA analyses for the above three injector/mixer concepts
- Developed an effective piezoelectric driver for investigation of both continuous and pulsed fuel injection applications
- Tested and refined mixing chamber configurations for each injector concept to achieve uniform feed stream distributions for optimal reformer performance

Future Directions

- Finish design and fabrication of a pre-heating simplex injector for performance evaluation
- Complete high temperature rig tests and laser diagnostics for the remaining injector/mixer concepts
- Compare performance data for all four injection concepts and down select the most promising design for various diesel fuel reforming applications
- Utilize statistical design-of-experiment techniques to establish correlation equations for the most promising injector concept
- Investigate effect of spray pulsation on mixture pattern, circumferential uniformity and temperature distribution
- Incorporate carbon-tolerant design features to enhance injector/mixer service life

Introduction

Fuel processors are a very important component of SOFC systems, enabling them to compete with other auxiliary power units (APU) in remote stationary and mobile power generation markets. Current state-of-the-art fuel processors are limited to using gaseous fuels, such as natural gas, hydrogen and liquefied petroleum gas (LPG). In the near term, however, liquid hydrocarbon fuels are the preferred choice for SOFC power systems because of their availability and existing distribution networks.

Currently, the liquid fuel reforming technology is not yet viable for commercial applications. One of the major technical barriers for liquid fuel processing is reactor durability. The performance of the reforming catalysts quickly deteriorates as a result of carbon deposition, sulfur poisoning and loss of precious metals due to sintering or evaporation at high temperatures. To mitigate these problems, numerous studies are being conducted to optimize catalyst materials and reactor design/operation.

One of the engineering approaches that could immediately offer some benefits towards alleviating problems associated with liquid fuel reforming is to improve feed stream preparation. Poor feed stream preparation such as inadequate atomization, wall impingement, and non-uniform mixing could easily lead to local conditions which favor carbon deposition and formation of hot spots in the reactor. Because liquid fuels are difficult to reform, a proper selection of injection and mixing systems for feed stream preparation plays an essential role in the development of reliable and durable liquid fuel processors.

Approach

In a typical ATR and CPOX reactor, liquid fuel is injected into preheated steam and/or air streams near the top of a mixing chamber. The liquid fuel must evaporate and be thoroughly mixed with the surrounding steam and air within a short distance prior to entering the catalytic reactor. During operation, the injection and mixing system must be able to accommodate varying power demands in a relatively short response time. In most mobile APU applications, there are very limited inlet pressures available for liquid atomization and feed stream mixing, making it especially challenging for the design and development of fuel injection/mixing systems.

This program focuses on developing several integrated injector/mixing chamber systems suitable for diesel fuel reforming in SECA applications. Four different injection concepts are being evaluated for their performance and limitations, including a multipoint impingement injector, a gas-assisted simplex injector, a high-energy piezoelectric injector and a preheating simplex injector. Analytical tools and advanced experimental instruments are utilized to help characterize the flow field structure and refine the injector and mixing chamber design.

CFD analysis is conducted to predict injector flow rates, pressure drops and upstream flow uniformity to reduce development iterations. It is also used to assess the overall flow field structure and mixing capability at high temperatures. In addition, finite element thermal analysis is performed to determine the distribution of metal temperature for the assessment of internal coking, steam

condensation, material growth and excessive stresses.

A steam/hot air test rig has been constructed to facilitate the injector and mixing chamber development. Injector flow rates can be accurately calibrated to meet reformer requirements at high temperatures. During development, the test rig is also useful for conducting flow visualization and for preliminary screening of various injector concepts and design modifications. More detailed measurements are conducted at ambient and high temperatures using advanced laser diagnostic techniques including phase/Doppler interferometry, Raman spectrometry and laser extinction tomography. These measurements provide flow field parameters such as droplet size, droplet velocity, flow pattern, uniformity index, mixture concentration and temperature, which are all critical for injector/mixing chamber evaluation.

In addition to developing injector/mixing chamber concepts, this project also plans to investigate the effect of pulsed excitation on fuel flows for evaluation of reduced power consumption and to incorporate carbon-resistant design features for extended service life.

Results

To date, three injection concepts have been designed and fabricated for performance evaluation. Experimental tests were conducted at both ambient and high temperature conditions that are representative of the fuel reformer operation. These tests were designed to examine the effects of injector designs, mixing chamber configurations, fuel properties and feed stream operating conditions on mixture characteristics and flow field structure. The results were used to help refine the injector/mixer performance. Figure 1 shows the mixture characteristics of an excellent feed stream preparation produced by a multipoint impingement injector/mixer system near the mixing chamber exit.

A porcupine thermocouple device was mounted near the exit of the injector/mixing chamber to determine the temperature distribution across the flow field at nine different radial locations. Flow field uniformity was evaluated using a uniformity index defined by the following formula:

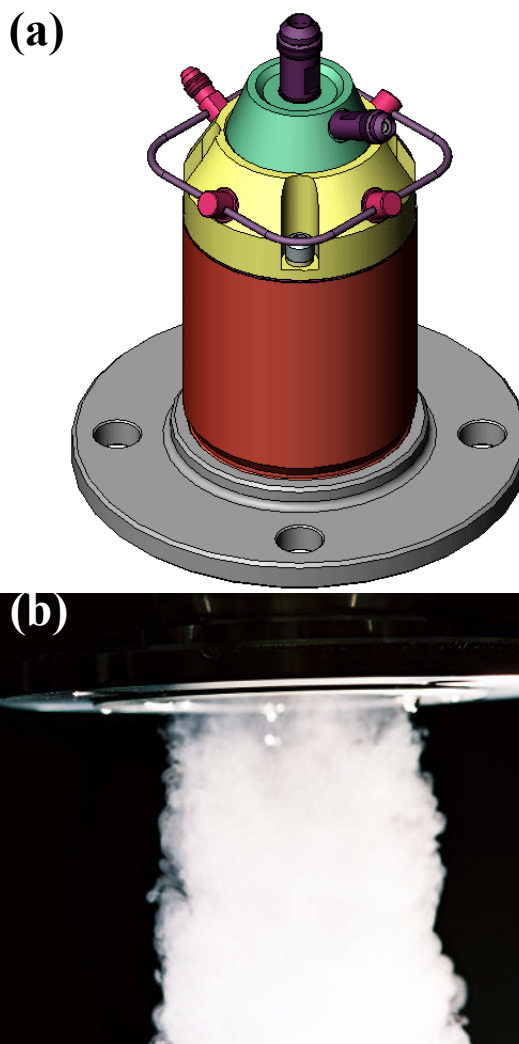


Figure 1. Fuel Mixture Characteristics Produced by a Multipoint Impingement Injector/Mixer System

$$\text{Uniformity Index} = (\text{max. temperature} - \text{min. temperature}) / \text{average temperature}$$

Table 1 lists the temperature results for a multipoint impingement injector/mixer system at 1 inch downstream from the chamber exit. For a multipoint impingement injector, the temperature field appears to be quite uniform for all test points because the uniformity index is less than 5%.

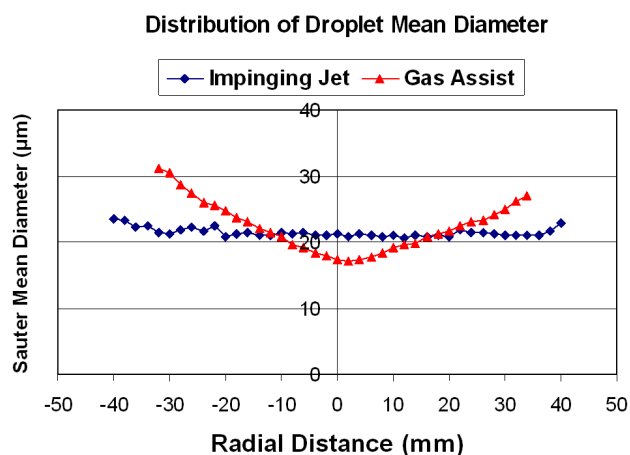
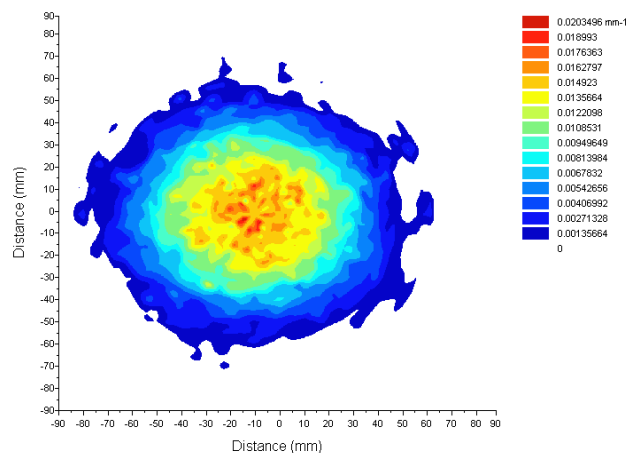
To examine wall impingement and droplet evaporation, spray characterization was conducted in an ambient environment and measurements were obtained for droplet sizes, droplet velocities, angles, trajectories and volume fluxes. This information not only helps us understand flow field structure, but also establishes minimum acceptance criteria for injector

Table 1. Temperature Results for a Multipoint Impingement Injector/Mixer System

Test Point	Section A (1 inch Downstream)		
	Average Temperature (°F)	(Max.-Min.) Temperature (°F)	Uniformity Index UI (%)
Pt. 1 – Fuel 5 pph, Air 25 pph/ 930°F, Steam 10 pph/550°F	525	10	1.91
Pt. 2 – Fuel 1.5 pph, Air 7.5 pph/ 930°F, Steam 3 pph/ 550°F	551	23	4.17
Pt. 3 – Fuel 2 pph, Air 12 pph/ 930°F, Steam 5 pph/ 550°F	553	20	3.62

sprays. Figure 2 shows a comparison of droplet mean diameters between the impingement injector and gas-assist injector concepts. Although the two injector sprays exhibit different size distributions, both injector concepts meet the droplet size requirement of less than 30 μm at the simulated maximum flow condition for a typical 10-kW ATR reformer.

To investigate mixture uniformity, ten different mixing chamber configurations were constructed for flow field evaluation using the laser extinction tomography technique. Each mixing chamber configuration contained different mixing devices, such as a mixing swirler and multiple layers of mesh screens. Figure 3 illustrates the measured mixture pattern for an integrated gas-assist injector/mixing chamber that contains a double-swirler mixer. This mixture pattern exhibits excellent uniformity in the circumferential distribution. Test results indicated that mixing devices had a significant impact on mixture pattern. Each injector concept must be properly integrated with an optimized mixing chamber configuration and mixing devices in order to achieve the best mixture pattern for the reactor.

**Figure 2.** Comparison of Droplet Mean Diameters Between an Impingement Injector and a Gas-Assist Injector**Figure 3.** Uniform Mixture Pattern Produced by an Integrated Gas-Assist Injector/Mixing Chamber

For the injector/mixer system evaluation, the most valuable data was obtained in a high temperature environment from the Raman spectrometry instrument shown in Figure 4. During measurements, an intense laser beam was projected into the flow field to induce Raman radiation. The scattered Raman signals were collected by the spectrometer and a photo detector unit to determine the wavelength and signal intensity. The wavelength and light intensity can be used to identify the concentration of the gas species. This data allowed us to understand the effects of feed stream operating parameters on mixture distribution. Distributions of fuel, steam and nitrogen were plotted against the radial distances across the flow field to reveal the

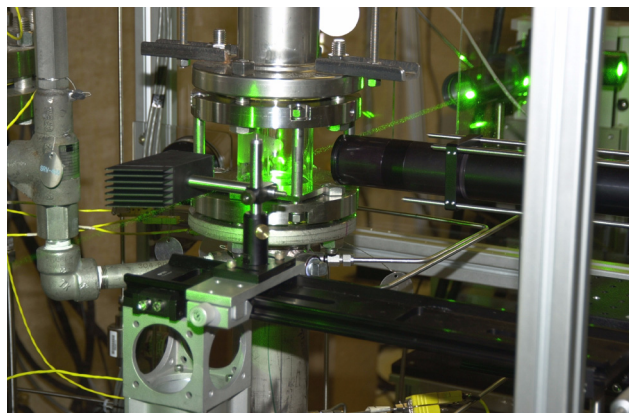


Figure 4. Raman Spectrometry Instrument Used for Measurements of Species Distribution

influence of fuel property, inlet pressure, inlet temperature, mixing chamber and mixing device on mixture uniformity for the selected injector/mixer designs.

Raman data indicated that the impingement injector provided relatively uniform species distribution. The signal quality, however, varied with feed stream operating conditions due to varying extent of carbon deposits on the quartz window. Since steam flow was utilized to atomize the diesel fuel, it had a major impact on fuel distribution. As the steam flow rate increased, fuel concentration was mostly distributed in the center field, with less severe carbon deposits on the wall. It was also observed that higher steam temperature appears to provide stronger Raman signals and more uniform species distribution across the flow field.

The investigation also revealed that fuel properties have a significant effect on the mixture distribution. A series of tests was conducted using the same injector/mixer for a back-to-back comparison between diesel and Jet-A fuels. Results indicated that the Raman signal strength for Jet-A fuel was much stronger than that of the diesel fuel. The distribution of Jet-A fuel appeared to be more uniform and more repeatable, signifying a more complete evaporation and mixing process.

Depending on the injector concepts, it was found that mixing devices could provide additional improvements to flow stability and mixture uniformity. For instance, the mixture uniformity was significantly improved by adding a central swirler

inside the mixing chamber for the gas-assist injection concept. For the impingement injector concept, however, adding mixing devices did not seem to provide any noticeable benefits.

Conclusions

The present investigation has generated a large database on the design and development of various injection and mixing systems. It contains information concerning the influence of the critical injector design/operation parameters on fuel mixture preparation. This engineering knowledge could immediately be applied to help alleviate problems associated with diesel fuel reforming, thereby improving reformer durability. Not only will this database help engineers understand the limitations of injection and mixing systems for diesel fuel processing, but it will also be used in further analyses of injector/mixer design optimization, manufacturing cost reduction and injector/reactor performance correlation. The following is a list of the major observations for the present study:

- The multipoint impingement injector produces fine droplets and uniform mixture pattern when a minimum of 2 psig inlet pressure is available from either the steam or airflow feed lines.
- The gas-assist injector is a simple and robust design that can also produce fine droplets and uniform mixture distribution with sufficient inlet air or steam pressures. Due to high droplet inertia, it requires a mixing chamber equipped with a central swirler to help stabilize the mixture flow.
- The high-energy piezoelectric injector is the best performer in fuel atomization for reformers with very limited steam or air inlet pressures. It has the potential to provide good atomization and mixing over a wide range of flow rates. However, the driver electronics need to be optimized to meet the requirement of low parasitic power consumption.
- It will be difficult to meet the stringent requirements of liquid fuel reforming using a single injection concept. The idea of a hybrid injection system or a pulsed modulated injection system may need to be explored in order to achieve low power consumption, adequate atomization and mixing. For example, a hybrid

piezoelectric/gas-assist injector may allow fuel reformers to operate for many hours and over a wide range of flow rates. Using this hybrid system, the piezoelectric injector would only be operated at low flow rate conditions to minimize power consumption, and the gas-assist injector would be utilized for high flow rate conditions.

Special Recognitions & Awards/Patents Issued

1. "An Integrated Fuel Injection and Mixing System for Fuel Cell Reformers", U.S. Patent application was filed on April 15, 2005.

FY 2005 Publications/Presentations

1. "Innovative Injection and Mixing Systems for Diesel Fuel Reforming", Presented at the Sixth Annual SECA Workshop, Pacific Grove, California, April 18-21, 2005.